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U. S. ARMY TEST AND EVALUATION COMMAND
COMMON ENGINEERING TEST PROCEDURE

INVESTIGATION OF MISSILE SYSTEM AERODYNAMICS

1. OBJECTIVE

The objective of this materiel test procedure is to describe the engineering tests required to obtain data on missile aerodynamics during actual flight conditions. Flight characteristics such as force and moment coefficients, heating effects and aeroelastic effects are to be determined. Preliminary missile parameters derived from analytical techniques and wind tunnel testing are verified and updated. Missile performance characteristics and flight safety boundaries are to be established.

2. BACKGROUND

The airframe of any missile or rocket is the delivery system of the payload (warhead) to the target. The performance of the airframe is primarily determined by the aerodynamic characteristics, hence the behavior of the aerodynamic system has to be investigated under the most realistic conditions. Test firing of a full scale model in the surrounding atmosphere fulfills this requirement.

2.1 DEVELOPMENT OF SYSTEMS AERODYNAMICS

The development of systems aerodynamics of a missile or a rocket can generally be divided into four phases:

a. Basic design by using fluid flow theory, other analytical methods and empirical techniques.
b. Windtunnel testing of subscale models of prototypes or components.
c. Flight simulation by subjecting a mathematical model of the physical system to parametric studies on analog, digital or hybrid computers.
d. Test flights of full scale models.

The nature of missile development renders this four-step process a continuous procedure in which each step complements, updates, and refines the airframe for the attainment of the required performance.

2.2 REQUIREMENTS FOR FLIGHT TESTING

A conclusive assessment of the entire missile system can be obtained only by flight-testing a sufficient number of production models and evaluating the results against given standards and/or specifications. Flight-testing of systems aerodynamics is mandatory for arriving at a valid and final quality statement.

The consolidated approach to engineering tests, as opposed to a sequential testing concept, results in possible verification or satisfaction

of engineering test requirements prior to manufacture of production prototype hardware. This is especially true for systems aerodynamics. Generally, however, the need for conducting special flight tests in order to investigate missile systems aerodynamics using production prototype models exists. The requirements for such special flight tests are outlined in (a) through (e) below.

a. Fluid Flow Theory and other analytical methods can provide aerodynamic data only to a limited degree because there exists no general theory of aerodynamics due to its nonlinear nature.

b. There is no substitute for full scale flight testing for achieving the final verification of performance characteristics and safety standards specified in the Qualitative Materiel Requirements and/or Technical Characteristics of missiles because wind tunnel testing can only furnish limited accuracy. The main reasons for this limited accuracy are problems concerning scale factors, model support, and shock reflections from the tunnel wall.

c. The feedback of aerodynamic flight data into the mathematical model (simulation model) for overall system evaluation is of vital importance.

d. Aerodynamic characteristics derived from full scale hardware tested during the development phase prior to engineering testing require verification and/or modification due to changes made to the missile configuration from engineering design models to production prototype models.

e. Flight safety boundaries established prior to production prototype hardware may require correction because the aerodynamic characteristics of the prototype model may have altered actual performance such that previously determined safety boundaries are no longer valid.

3. REQUIRED EQUIPMENT

a. A missile range whose size and facilities, such as launch sites, instrumentation, recovery, data recording, and data reduction equipment are compatible with the system under test.

b. Instruments required to measure flight characteristics necessary for computing aerodynamic parameters. The four basic instrumentation groups are: (1) Ground Based, (2) Missileborne, (3) Atmospheric Sensors, (4) Related Data Instrumentation.

c. Radars including DOVAP, velocimeter, monopulse, continuous wave, phased array, etc.

d. Optics, including fixed cameras, cinetheodolites, boresight cameras, infrared, etc.

e. Antennas, receivers, transmitters, recorders, etc.

f. Clock (Timing).

g. Pressure probes.

h. Temperature sensors.

i. Attitude measuring devices such as gyros, angle-of-attack meters, etc.

j. Accelerometers.

k. Strain gauges.

l. Potentiometers.

m. Special instruments such as stable platforms for use as a reference for guidance, hinge-moment indicators, ablation rate gauges, boundary-layer

transition indicators.

n. Transducers for transmitting outputs of missileborne instruments.

o. Data recorders for postflight test recovery.

p. Magnetic tape and instrument packages for jettisoning and parachute drop.

q. Fuel flow rate meter.

r. Vibration sensors.

s. Altimeters.

t. Atmospheric Sensors - these sensors are used to measure atmospheric state variables and other airspace characteristics of the environment in which the missile is operating. Different altitude levels require different sensing devices. These are listed below, including the respective data they are designed to measure:

1) Atmospheric Towers up to 500 feet height for measuring pressure, temperature, humidity, and wind velocity vector as input for launch data criteria.
2) Weather balloon for measuring pressure, temperature, and wind velocity vector (by ground tracking) between 500 feet and 100,000 feet above deck.
3) Sounding Rockets for measuring pressure and temperature from 100,000 feet to 220,000 feet above deck.

u. Scales for measuring missile weight, center of gravity and moments of inertia.

v. Motor chamber pressure gauges.

w. Documents and blueprints containing geometrical features and dimensions of the external configuration and other pertinent information.

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During Testing.
J. AMC Regulation 385-24, Range Safety.
K. MTP 3-1-002, Confidence Intervals and Sample Size.
L. MTP 5-1-020, Missile Flight Surveillance.
M. MTP 5-1-025, Dynamic Structural Data Analysis.
N. MTP 5-1-030, Simulation Studies of Missile and Rocket Systems.
O. MTP 5-2-504, Structural Testing for Nonoscillating Steady State and Transient Loads.
P. MTP 5-2-507, Vibration Test.
Q. MTP 5-2-509, Aerodynamic Heating.

5. SCOPE

5.1 SUMMARY

The procedures outlined in this MTP provide general guidance for obtaining data on missile aerodynamics. The MTP gives the uses of missile flight simulation, prescribes guide lines for the setup of ground instrumentation and data handling facilities, outlines preflight missile inspection procedures, prescribes installation of missileborne instrumentation, and enumerates meteorological support needs. Guidelines are given for reduction of data to obtain force and moment coefficients, aerodynamic heating effects, aeroelastic effects, and establishment of flight safety boundaries.

The procedures involve actual flight testing of missiles in the real environment of the airspace.

5.2 LIMITATIONS

These procedures apply to preproduction prototype and later models of rockets, guided and unguided missiles with a range of up to 200 miles ground track.

Prerequisites for these tests are adequate inputs from analytical computations, wind tunnel testing, and from previous model flight tests. For reasons of economy, it is not practical to determine all desired aerodynamic coefficients from flight tests, but only a limited number under selected flight conditions. These data are then used to spot-check and verify and possibly extrapolate the already existing information.

This MTP presents procedures covering the general case of a guided missile flight with the objective of obtaining aerodynamic coefficients, heating effects, and aeroelastic effects. For many tests only part of these data is required, especially for unguided missiles and rockets. In such cases the procedures are modified by merely omitting the nonrequired subprocedures.

6. PROCEDURES

6.1 PREPARATION FOR TEST

a. Prior to testing, study the test item as required to provide

information on background and statistical considerations for use in testing and analysis of test results.

1) Review design, operational, and instructional material for the test item.
2) Review aerodynamic reports of similar missile systems.
3) Prepare a test item sample plan to provide statistical confidence of final data. See MTP 3-1-002.
4) Prepare record forms for systematic entry of data and chronology of test.
5) Review safety SOPs to insure safety of personnel and equipment. See MTP 5-1-020 for general information germane to those functions of an established missile range which constitute an independent means of assuring safe impacts at all times.
6) Review security measures and SOPs to insure safeguarding classified materiel and data.

b. Select the best available instrumentation to obtain maximum information content from the test data.

c. Insure that test equipment is certified and calibrated according to pertinent Department of the Army Regulations.

d. Instruct test personnel as required to insure that they are familiar with the technical and operational characteristics of the test item.

e. Ascertain the availability of the safety statement for the test item as required per USATECOM Regulation 385-6.

f. Determine which data may be recorded on tape aboard the missile, and determine whether to jettison the tape or to recover it after impact.

6.1.1 Missile Flight Simulation

A mathematical model of the missile is generated using information accumulated during the earlier phases of its development. Typical trajectories are simulated on a computer (analog, digital or hybrid). See MTP 5-1-030 for general information germane to simulation studies of missile and rocket systems. Simulation results permit (1) selection of the proper test range by establishing a nominal trajectory, (2) type and amount of instrumentation, and (3) criteria for missile flight safety.

6.1.2 Ground Instrumentation

a. Set-up and put into readiness status in accordance with procedures sepcified in MTP 5-1-020:

1) Radars for acquisition and tracking.
2) Optical equipment (cameras, infrared, cinethoedolites, etc.).
3) Telemetry ground equipment (receivers, antennas, recorders, etc.).
4) Atmospheric measuring equipment (radiosonde, balloons, sounding rockets, etc.).

b. Activate atmospheric measuring equipment (radiosonde, balloons, sounding rockets, etc.) prior to launch of the missile as close to launch time as practical.

6.1.3 Data Handling

Set-up and put into readiness status:

a. Data recording and storing equipment.
b. Communication chain (Kineplex, Telephone wire).
c. Computers for Real Time computation and Postflight analysis (digital and hybrid).

6.1.4 Missile Inspection

a. Inspect missile for any external damage and other obvious anomalies.
b. Check vital subsystems and components for malfunctions, using necessary test equipment and prescribed check-out procedures. Emphasis should be put on fail-safe mechanism for missile flight safety purposes.
c. Measure and record all pertinent physical dimensions and other characteristics such as: length, diameter, number of fins, coating material (paint, teflon, etc.), surface roughness, weight, center of mass location, moments of inertia, location of transducers (pressure gauges, thermistors, strain gauges, gyros, accelerometers, etc.) and any modifications or changes with respect to the basic design (blueprint). Make photographs, scale-drawings and weight and balance sheet of test specimen.

6.1.5 Missileborne Instrumentation

a. Some of the instruments listed are standard equipment and therefore they may be already installed in the missile. Minor changes in the circuitry can avoid duplication of instruments. Generally, the following instruments have to be installed for aerodynamic testing:

1) Stagnation pressure gauge (or Pitot-tube)
2) Static pressure gauge
3) Temperature sensors (stagnation and skin)
4) Accelerometers (translational motion)
5) Rate gyros (rotational motion)
6) Base pressure pickup (power-off condition)
7) Motor chamber pressure gauge (propulsion)
8) Receiving and transmitting antennas (guidance)
9) Missileborne magnetic tape and instrument packages

b. Special tests may require other instruments such as those listed in 1) through 11) below. The use of these has to be determined for each case:

1) Angle-of-attack meter
2) Selected pressure pickups on body surface
3) Altimeter (mechanical or electronic)

4) Strain gauges for aeroelastic effects
5) Boundary layer sensors
6) Vibration sensors
7) Ablation rate gauges
8) Fin position indicator (potentiometer)
9) Hinge moment meter
10) Fuel flow rate meter
11) Beacon or transponder

6.2 TEST CONDUCT

It is a unique feature of missile flight testing that relatively few procedures are involved during the actual test conduct as compared with test preparation and data reduction and analysis. The prime reasons for this, of course, are the remoteness and high speed of the test object. The main activity during the test is usually limited to data acquisition, collection, and recording. All events must be recorded in a common time frame, preferably lift-off time. Basically, there are two groups of missile systems to be considered with regard to missile system aerodynamics; namely, unguided and guided. The general procedure described below is valid for both cases; however, certain steps, identified by the label (G), are to be deleted for tests of unguided missiles.

Record the complete countdown procedure and retain it for reference. At exact lift-off, set event timer to zero (0). Record the following flight events:

a. Ignition (first stage).
b. Launch (lift-off, T_{LO} = X).
c. Enablement (if applicable).
d. Booster (first stage) burnout.
e. Booster separation.
f. Sustainer (second stage) ignition.
g. Sustainer burnout (or cutoff).
h. (G) Control command.
i. (G) Control execution.
j. Intercept and/or impact.
k. Special events.

1) Special maneuvers
2) Catastrophic failures

l. Recovery of missile and/or components.
m. Motion of missile CG (measured by ground based instrumentation).

1) Missile position
2) Missile velocity

n. Vehicle information (measured by missileborne instrumentation and transmitted via telemetry channels or recorded by on board magnetic tape).

1) Linear accelerations
2) Angular velocities
3) Roll position
4) Angle-of-attack
5) Stagnation pressure
6) Surface pressures, including base pressure
7) Surface temperatures
8) Motor chamber pressures (all stages)
9) Fin positions
10) Hinge moments
11) Ablation rates
12) Fuel flow rate
13) Other air frame characteristics

6.3 TEST DATA

NOTE: All data points and events are recorded with reference to lift-off time (T_{LO} = X) which in turn is synchronized with the range-time scale. Range-time is usually geared to Z-time, commonly known as Greenwich Mean Time (GMT).

6.3.1 Important Events To Be Recorded

a. Ignition (first stage)
b. Lift-off (T_{LO} = X = 0)
c. Enablement (if applicable)
d. Booster burnout (or cut-off)
e. Booster separation
f. Sustainer ignition (second stage)
g. Sustainer burnout (or cut-off)
h. Intercept (or impact)
i. Special events

1) Uncontrolled maneuvers
2) Catastrophic failures

6.3.2 Internal Measurements (Missileborne Instrumentation)

The following information is needed for the aerodynamic evaluation of the missile and may be transmitted to the ground via FM Telemetry channels and recorded on analog or digital tape, or it may be recorded on board the missile on magnetic tape and recovered after impact or by jettisoning the tape package.

a. Angle-of-attack
b. Stagnation pressure
c. Selected surface pressures
d. Selected surface temperatures
e. Body accelerations
f. Body rotations

g. Ablation rates
h. Base pressure
i. Motor chamber pressure (for all stages)
j. Fin positions
k. Hinge moments
l. Fuel flow rate
m. Airframe (panel) vibrations (frequencies and amplitudes)
n. Panel load measurements (strain, stress, bending, etc.)
o. Other, as required for particular systems.

6.3.3 External Measurements (Ground Instrumentation)

Data obtained from external sources consist mainly of trajectory information. Limited information can also be collected concerning missile attitude and orientation.

a. Radars yield data in discrete manner (sample rate varies usually from 30 to 100 per second) to be recorded on digital tape such as: position in three components; i.e., azimuth, elevation, and range.
b. Velocimeters measure missile radial velocity in ft/sec and limited angular orientation.
c. Fixed cameras. Cameras with 70mm frame size are used to record missile motion on and near the launcher to detect tip-off effects, roll-angles, etc., during the first phase of the flight. Quality of these data deteriorates with distance from launch site.
d. Movie cameras (Cinetheodolites, etc.). Frame rate varies from 30 to 2000 frames/sec. Frames carry accurate time tage which permit detailed analysis of the dynamic behavior of the airframe such as booster separation, roll position, control surface motion, and event sequence of catastrophic failures. Some cameras are equipped with angular measuring devices (boresight cameras) and can therefore be used for a position fix in conjunction with other instruments, (cameras or radars).

6.4 DATA REDUCTION AND PRESENTATION

The major groups of aerodynamic data to be reduced from flight test are:

a. Force and moment coefficients
b. Aerodynamic heating effects
c. Aeroelastic effects

6.4.1 Force and Moment Coefficients

The determination of these coefficients is the prime objective of aerodynamic flight testing. It is common practice in aerodynamics to derive and use nondimensional coefficients rather than forces and moments. The main reason for this is the easy application of scale modeling and comparison with analytical data. The force and moment coefficients are of the general form:

$$C_F = \frac{F}{qS} \qquad (1)$$

$$C_M = \frac{M}{qSd} \qquad (2)$$

where:

- C_F - the force coefficient.
- C_M - the moment coefficient.
- F - the aerodynamic force in pounds
- M - the aerodynamic moment in pounds feet
- q - dynamic pressure in pounds per square foot
- S - reference area in square feet, normally the base area of the missile.
- d - reference length in feet, normally the base diameter of the missile.

As indicated by equations (1) and (2), nondimensionalization is achieved by dividing the forces and moments by some typical flow parameter and physical dimensions. Since raw data are normally given on a common time scale (range time) and engineering evaluation is concerned with the physical significance of the test, it becomes necessary to compute first certain parameters versus which the aerodynamic coefficients have to be plotted. Extreme care must be exercised to insure that prior to any analysis all data are compatible with respect to physical dimensions and geometrical reference frames. The more important parameters are listed in 6.4.1.1. Similarly the more important coefficients and other characteristics are shown in 6.4.1.2.

6.4.1.1 Parameters

a.	M	Mach number (1)
b.	Re	Reynolds number (1)
c.	q	dynamic pressure (lb/ft²)
d.	H	altitude (ft)
e.	α	angle of attack (pitch) (degrees)
f.	β	angle of attack (yaw) (degrees)
g.	φ	roll angle (degrees)

6.4.1.2 Coefficients and Other Characteristics

a. Lift (or normal force)
b. Drag (or axial force)
c. Moment in pitch, yaw and roll
d. Damping in pitch, yaw and roll
e. Magnus force
f. All other stability derivatives as required
g. Center of pressure location
h. Boundary layer transition
i. Boundary layer separation results

6.4.2 Aerodynamic Heating Effects

Virtually all missiles operate in the supersonic flight regime during the major portion of their trajectory. The resulting friction with the surrounding air causes high heating rates, which in turn put severe stress on skin material. The effects of this high temperature environment on missile structures are treated in detail in MTP 5-2-509.

The procedures of MTP 5-2-509 determine aerodynamic heating effects using laboratory methods. The procedures of this MTP determine aerodynamic heating effects using actual measured trajectory parameters from flight tests. However, the theoretical considerations and the mathematics involved are the same, only the source of the input data differs. Therefore, refer to MTP 5-2-509, Appendix A to determine the thermal environment. Replace the computed mission profile specified in MTP 5-2-509 with the actual measured trajectory parameters obtained from the flight test. Paragraph 6.4.2.1 lists the parameters and state variables derived from flight tests which replace the input data specified in MTP 5-2-509.

6.4.2.1 Parameters and State Variables

a. M - - - - - - - - Mach number
b. Re - - - - - - - - Reynolds number
c. Pr - - - - - - - - Prandtl number
d. Nu - - - - - - - - Nusselt number
e. H - - - - - - altitude
f. q - - - - - - dynamic pressure
g. T_∞ - - - - - - free stream temperature
h. T_s - - - - - - stagnation temperature
i. T_b - - - - - - body temperatures
j. P_b - - - - - - surface pressures
k. P_∞ - - - free stream pressure
l. $\dot{r}_a$ - - - - - - ablation rate
m. C_f - - skin friction coefficient

6.4.3 **Aeroelastic Effects**

The discussion and mathematical treatment of the force and moment coefficients in paragraph 6.4.1 are based on the assumption of rigid body behavior, i.e. that the exterior configuration is unchanged. During actual flight, however, the missile is subject to varying degrees of deformation. These deformations or aeroelastic effects can be either oscillatory or steady state and are commonly known as flutter, vibration, buffeting, bending, and [illegible]. Due to these deformations the aerodynamic coefficients could be modified sufficiently to degrade the effectiveness of the entire missile system.

Aeroelastic effects are a peripheral field of aerodynamics. Their evaluation lies within the field of structural analysis. Refer to MTP 5-1-025 for the mathematical analysis of flutter, vibration and buffeting effects, to [illegible] for the mathematical analysis of steady state loads causing bending

and torquing, and to MTP 5-2-507 for the mathematical analysis of effects of vibrations on the airframe.

The procedures of MTPs 5-2-504 and 5-2-507 arrive at evaluations using data derived from laboratory methods. The procedures of this MTP obtain data on aeroelastic effects using actual in flight variables and parameters. The theoretical considerations and the mathematics offered in MTPs 5-1-025, 5-2-504, and 5-2-507 are the same, only the source of the input data differs. The data requirements in referenced MTP's can be satisfied with the data obtained through actual flight tests. Paragraphs 6.4.3.1 and 6.4.3.2 list the variables and the parameters derived from flight tests.

6.4.3.1 Variables

a. P_f - - - - - - - - panel oscillation frequencies
b. P_a - - - - - - - - panel oscillation amplitudes
c. S_b - - - - - - - - body bending strains (lateral deformations)
d. S_t - - - - - - - - body torquing strain (torsional deformation)
e. C_d - - - - - - - - control surface deformations

6.4.3.2 Parameters

The variables listed in 6.4.3.1 are to be plotted versus the following parameters:

a. V_M - - - - - - - - missile velocity
b. H - - - - - - - - altitude (air density)
c. q - - - - - - - - dynamic pressure
d. T_b - - - - - - - - body temperature

6.4.4 Performance and Flight Safety Boundaries

The reduced data discussed in 6.4.1, 6.4.2, and 6.4.3 can now be used as an input for evaluation of missile performance, and determination of flight safety boundaries.

GLOSSARY

1. Aerodynamics: The science of the interactions and relationships between a flying vehicle and its surrounding atmosphere.

2. Fluid Flow Theory: The mathematical description of the behavior and characteristics of a fluid in motion.

3. Boundary Layer: The region of flow between a body surface and the potential flow field.

4. Boundary Layer Transition: Sudden change from laminar mode to turbulent mode.

5. Angle of Attack: The angle between the longitudinal axis of the missile and the velocity vector.

6. Ablation: Reduction and dissipation of surface material by aerodynamically generated heat.

7. Hinge Moment: Moment about the hinge of a control surface generated by aerodynamic forces.

8. Enablement: During launch, the missile control system is sometimes held inoperative. Enablement is the release of the control mechanism.

9. Magnus Force: Force, normal to the longitudinal axis of the missile, generated by a rolling motion while experiencing an angle of attack.

10. Stability Derivatives: The rates of change of the force and moment coefficients with respect to linear or angular velocity components of the missile or their time derivatives.

11. Center of Pressure: Intersection of a missile's longitudinal axis and resultant aerodynamic force vector.

12. Mach Number: $M = \frac{V_M}{V_s}$; ratio of missile velocity and speed of sound.

13. Reynolds Number: $Re = \frac{V_M d}{\nu}$; ratio of inertia forces to the viscous forces in a fluid flow.

14. Prandtl Number: $Pr = \frac{C_p \mu}{K}$; ratio of viscous shear work to thermal heat conduction.

15. Nusselt Number: $Nu = \frac{hx}{K}$; nondimensional heat transfer parameter (see MTP 5-2-509).

16. <u>Panel</u>: Structural skin section of the airframe.

17. <u>Stagnation Point</u>: Point on the missile surface, where the relative airspeed is zero and pressure and temperature are maximum.

18. <u>Base Area</u>: Region at the tail of the missile, where under-pressure is prevailing, adding to the drag. This drag component is usually higher for power-off condition than for power-on condition.

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13. ABSTRACT

This Engineering Test Procedure describes test methods and techniques for obtaining data on missile aerodynamics during actual flight conditions. Flight characteristics such as force and moment coefficients, heating effects and aeroelastic effects are determined. Preliminary missile parameters derived from analytical techniques and wind tunnel testing are verified and updated. Missile performance characteristics and flight safety boundaries are established.

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